



# Mach-Zehnder Interferometry in a Persistent-Current Qubit

Leonid Levitov

Argonne Miniconference, Nov 14, 2005

Experiment:

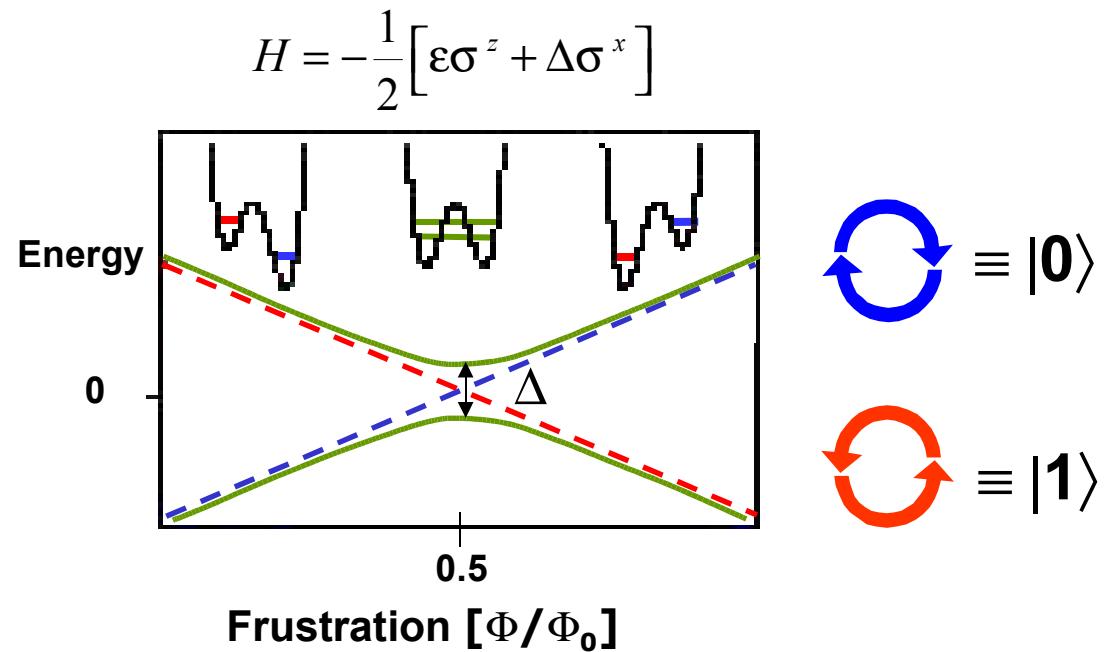
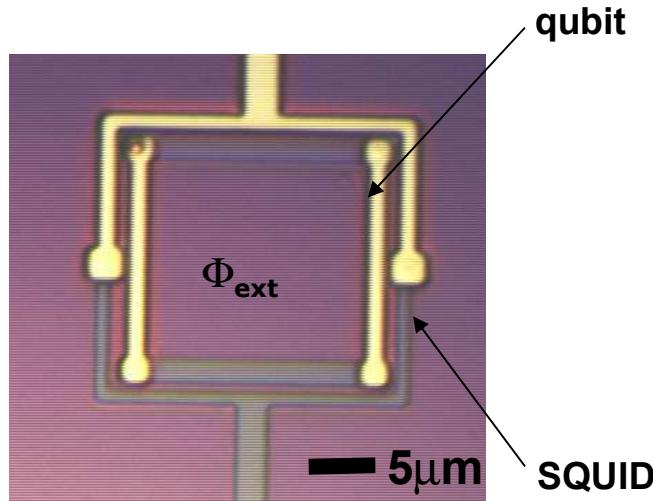
Will Oliver, Yang Yu, Janice Lee, Karl Berggren, LL, Terry Orlando

LANL archive: <http://arxiv.org/abs/cond-mat/0508587>

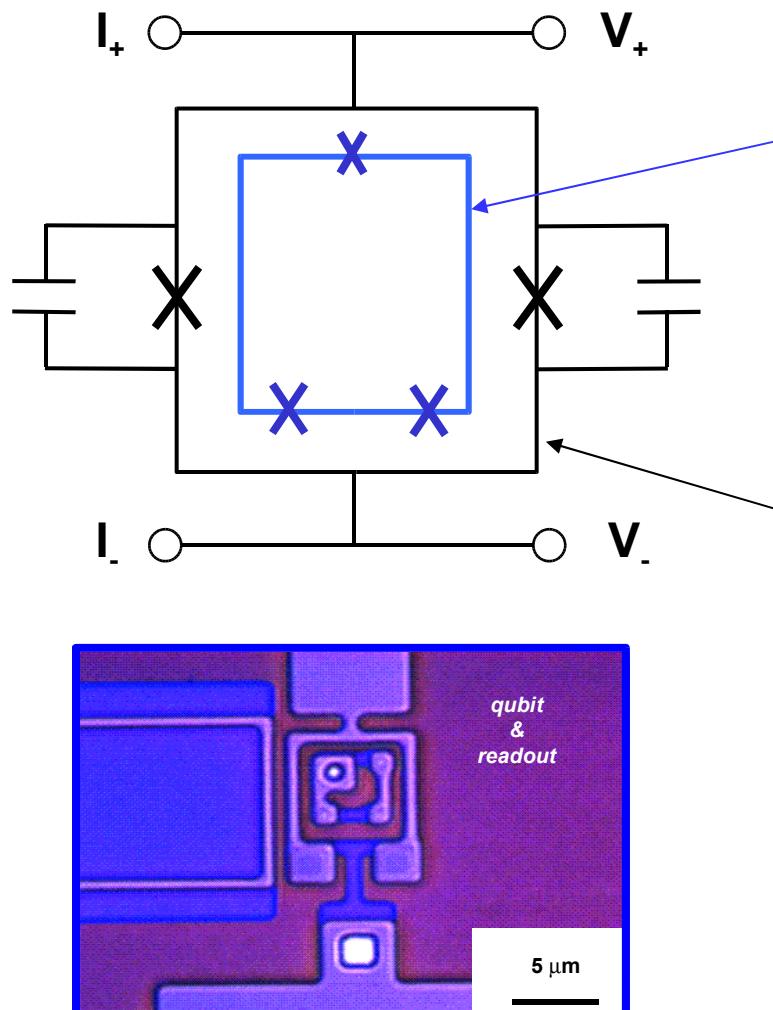
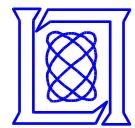
Science: <http://www.sciencemag.org/cgi/content/abstract/1119678>



- **Niobium persistent-current (PC) qubit**
  - Three-junction loop, one junction smaller by factor  $\alpha$
  - Double-well potential profile (tuned by frustration)
  - States: opposite circulating current
- **Qubit readout via DC SQUID magnetometer**
  - Magnetic field due to circulating current in qubit



Sample fabricated at MIT-LL



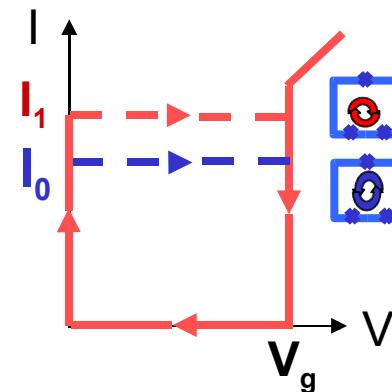
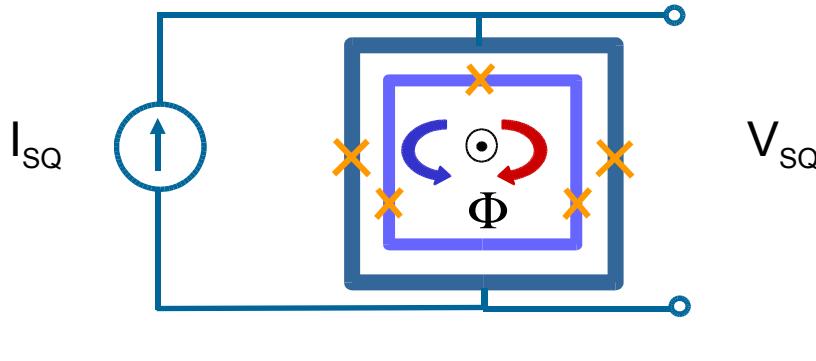
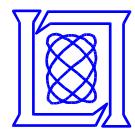
- **Three-junction qubit**

- JJ size:  $0.58, 0.65 \mu\text{m}$
- Loop area:  $16 \times 16 \mu\text{m}^2$
- Loop inductance:  $40 \text{ pH}$
- Circulating current:  $0.4 \mu\text{A}$

- **DC SQUID readout**

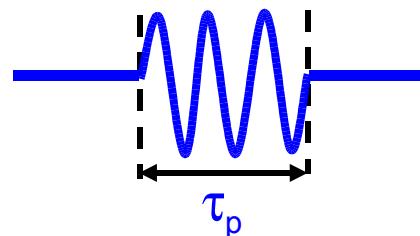
- JJ size:  $1.3 \mu\text{m}$
- Capacitors:  $1 \text{ pF}$
- Loop area:  $20 \times 20 \mu\text{m}^2$
- Loop inductance:  $50 \text{ pH}$
- Mutual inductance:  $20 \text{ pH}$
- Critical current:  $5 \mu\text{A}$
- Critical curr. density:  $1.5 \mu\text{A}/\mu\text{m}^2$

Samples are in Nb  
and made at MIT-LL



1. Preparation: just wait for equilibration ( $\sim 5$  ms)

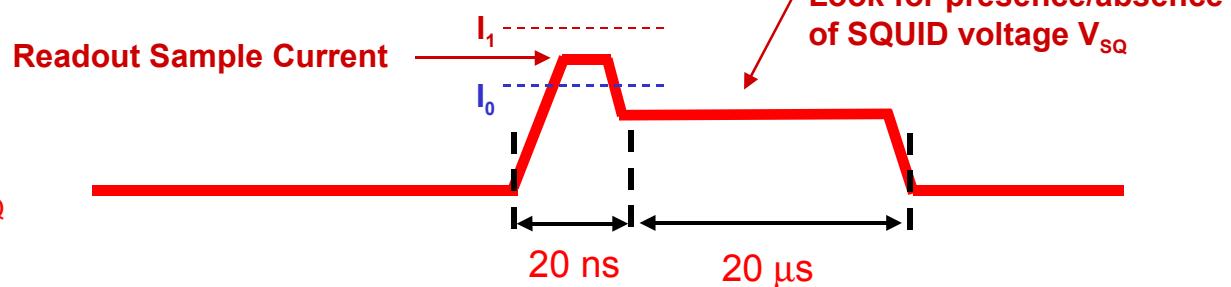
2. Apply Microwave Pulse



$$\tau_p = 10 \sim 100 \mu\text{sec}$$

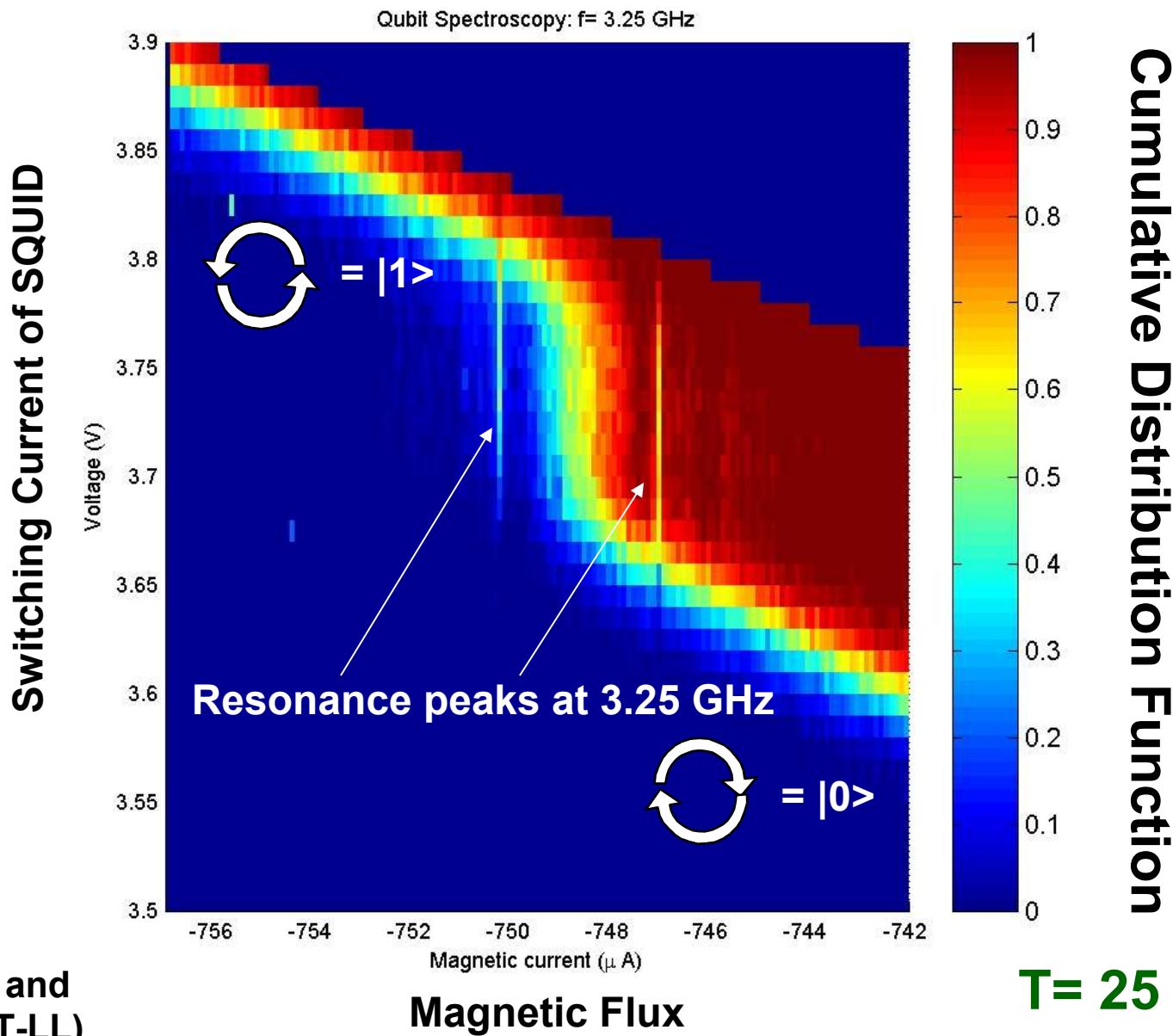
$$\nu = 1 \sim 20 \text{ GHz}$$

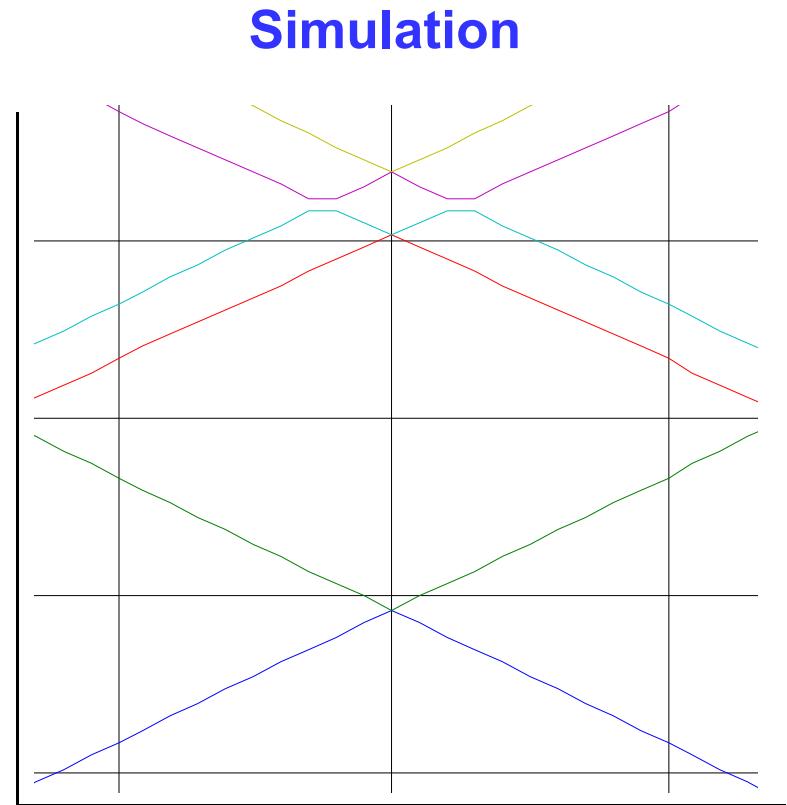
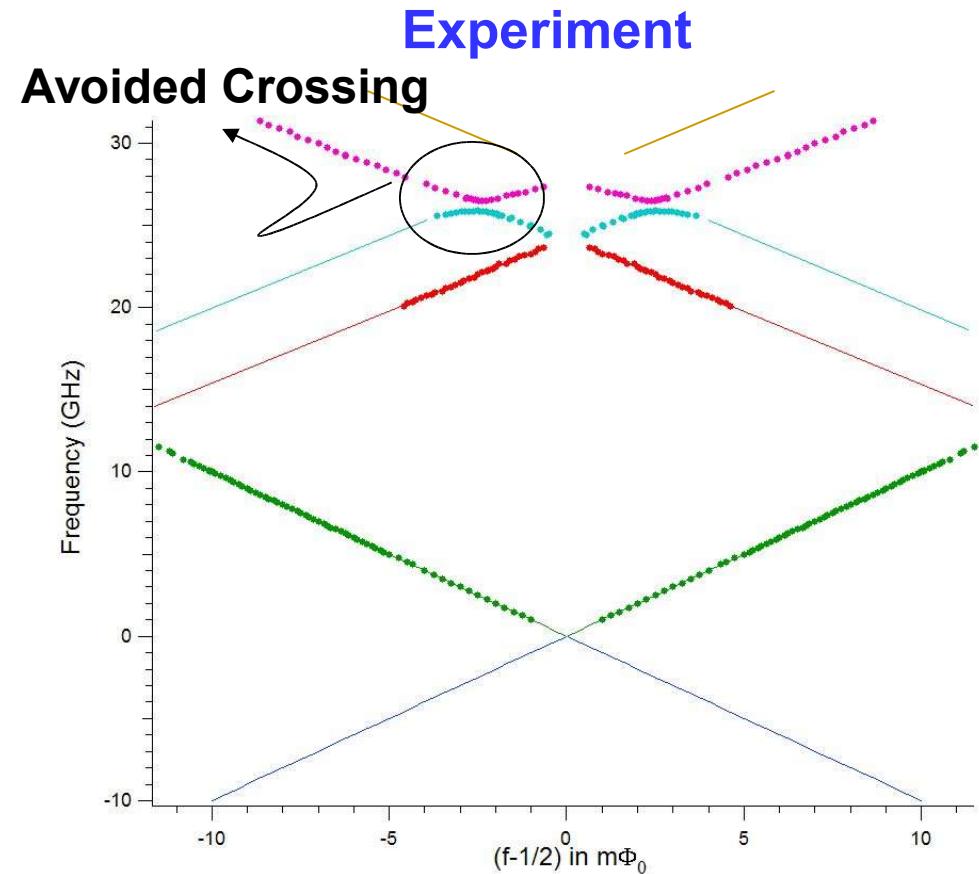
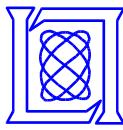
3. Pulse SQUID Current  $I_{SQ}$



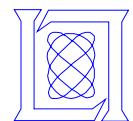
4. Repeat to gather statistics. **Vary qubit frustration and SQUID pulse amplitude** to form qubit switching cumulative distribution function.

# Cumulative Distribution Function: Weakly-Driven limit, 3.25 GHz

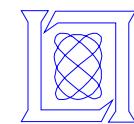




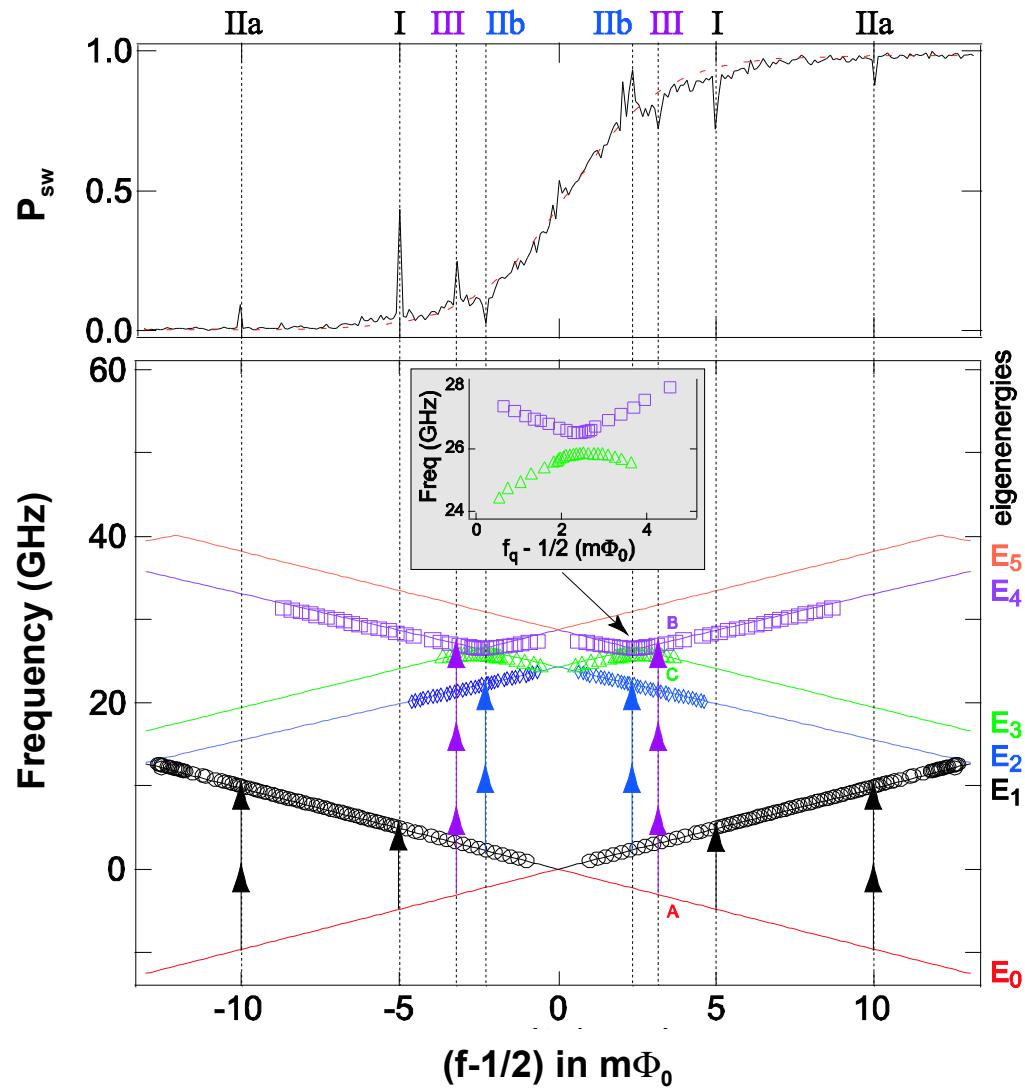
- Spectroscopy data
  - 15 mK @ MIT
- Simulation Parameters
  - 0.58, 0.65 mm JJs
  - $\alpha \sim 0.8$

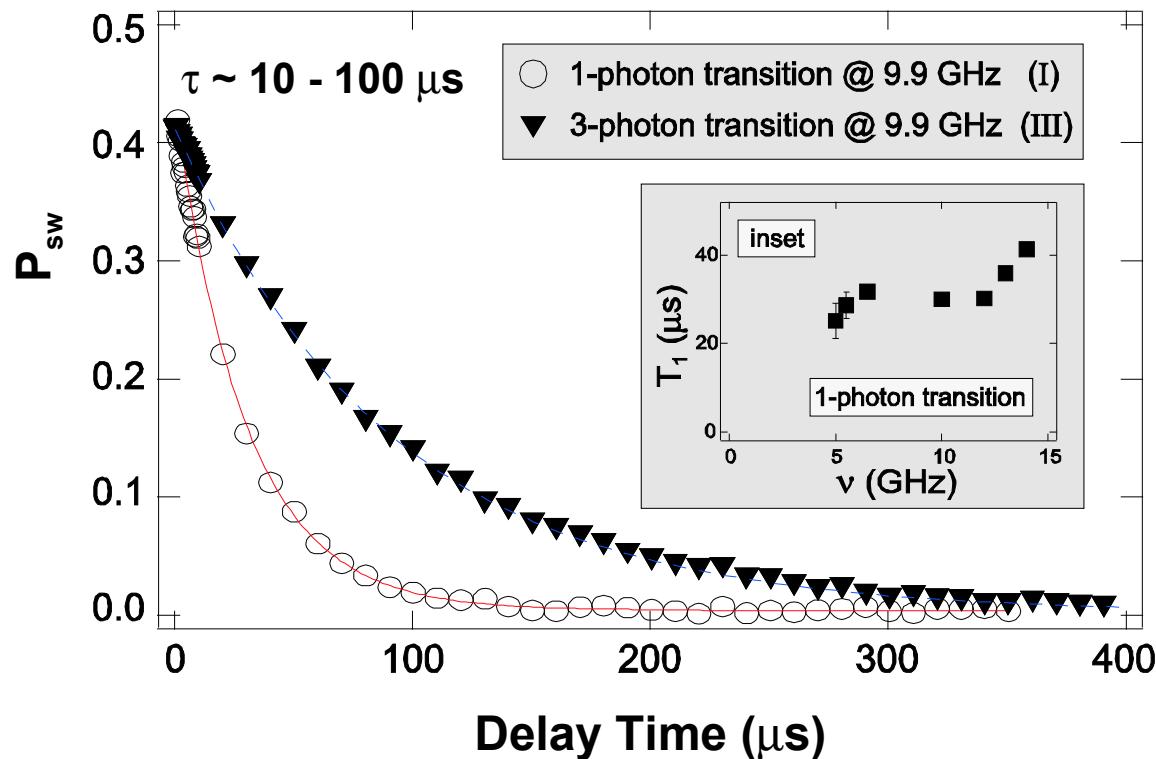
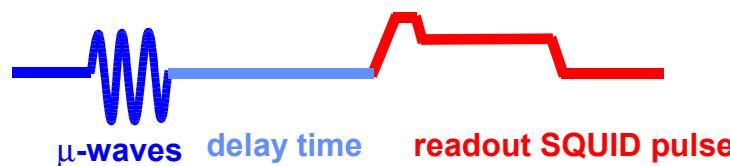
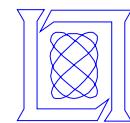


- **Multi-photon, Multi-level Spectroscopy and Rabi Oscillations**
- **Mach-Zehnder Interferometry, Bessel Ladder**

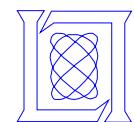


- **1D switching probability**
  - Resonance position
  - $|\Delta\nu|/|\Delta f| = 1/n$  GHz/m $\Phi_0$
  - $n$  = photon number
  - Energy band diagram
- $E_0$  to  $E_1, E_4$ 
  - I: single-photon
  - IIa: two-photon
  - III: three-photon
- $E_1$  to  $E_2$ 
  - IIb: two-photon

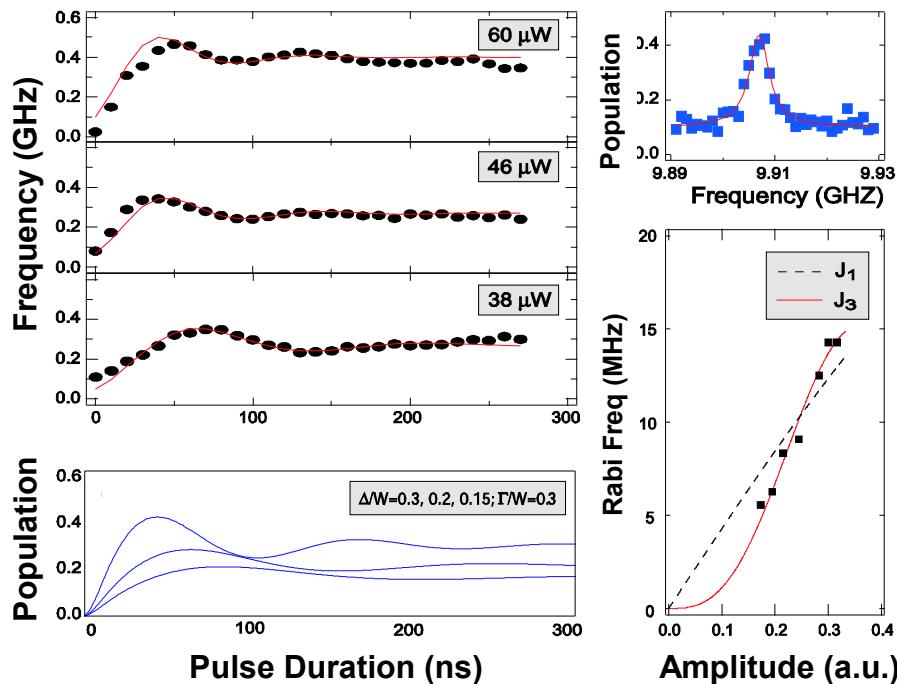




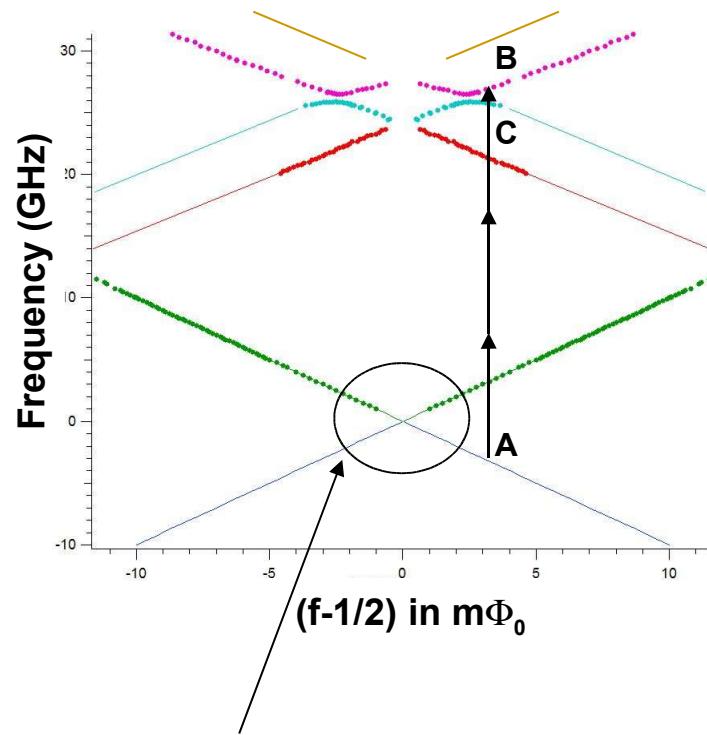
# Multi-photon, Multi-level Rabi Oscillation



Three-photon Rabi Oscillation Data  
Ground to Fourth Excited State

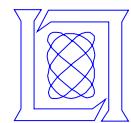


Experimental Energy Band Diagram



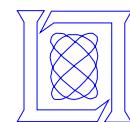
- Drive levels A and B
- Level B also couples to level C
- Narrow window of amplitudes / Rabi oscillations
  - Multi-photon, multi-level dynamics

$\Delta \sim 20$  MHz: JJs too large  
Require deep submicron JJs



- Multi-photon, Multi-level Spectroscopy and Rabi Oscillations
- Mach-Zehnder Interferometry, Bessel Ladder

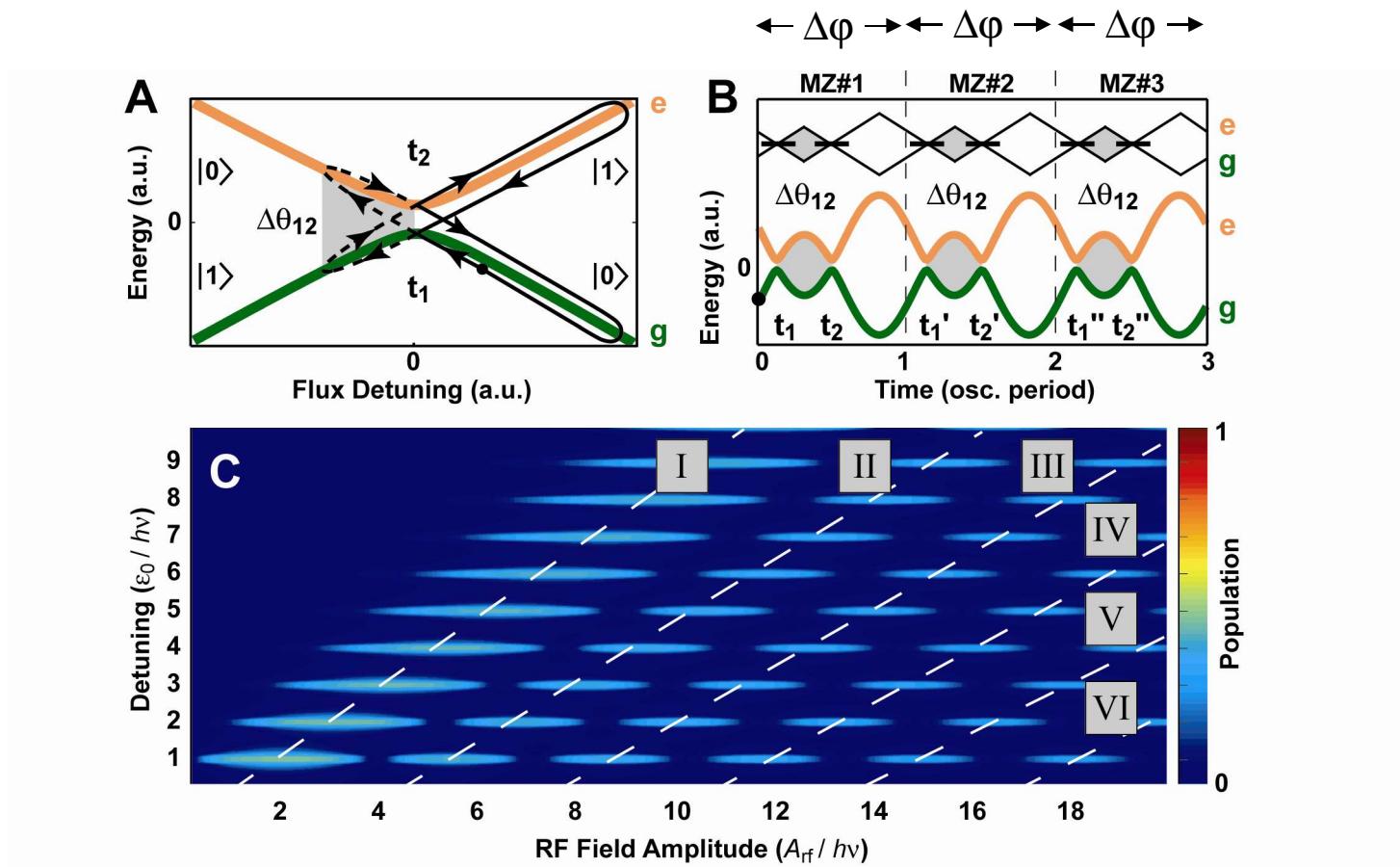


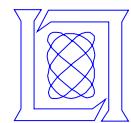


**Strong harmonic driving: Two Landau-Zener transitions / period**

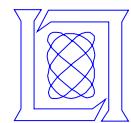
**Resonance condition:**  $\Delta\phi = 2\pi n$

**MZ interference phase:**  $\Delta\theta_{12}$





- **Mach-Zehnder Interferometry**
  - Two paths in qubit phase space, not position space
  - Landau-Zener transition as beamsplitter
  - Decoherence --> use high driving frequency
  - Multiphoton resonances
- **Physics**
  - Quantum coherence: oscillations with RF power
  - Similar to Stuckelberg oscillations (recurrent LZ transitions)
  - MZ fringes described by Bessel ladder
  - Use to find RF power on the sample, similar to Rabi osc



## Landau–Zener interferometry for qubits

A. V. Shytov<sup>1,2</sup>, D. A. Ivanov<sup>3,\*</sup> and M. V. Feigel'man<sup>1</sup>

<sup>1</sup>*L. D. Landau Institute for Theoretical Physics, Moscow 117940, Russia*

<sup>2</sup>*Institute for Theoretical Physics, University of California at Santa Barbara, USA*

<sup>3</sup>*Institute for Theoretical Physics, ETH-Zürich, CH-8093, Switzerland*

One may probe coherence of a qubit by periodically sweeping its control parameter. The qubit is then excited by the Landau–Zener (LZ) mechanism. The interference between multiple LZ transitions leads to an oscillatory dependence of the energy absorption rate on the sweeping amplitude and on the period. This interference pattern allows to determine the decoherence time of the qubit. We introduce a simple phenomenological model describing this “interferometer”, and find the form of the interference pattern.

|110490 v2 12 Dec 2003

During the last few years, a number of proposals for constructing quantum bits (qubits) from mesoscopic Josephson junctions have appeared [1, 2, 3, 4] and first experimental results in this direction have been reported [5, 6, 7, 8, 9, 10, 11]. Large part of these qubits are actually different physical realizations of an externally controllable quantum double-well system, with nearly equal depths  $E_{1,2}$  of both wells  $|E_1 - E_2| \ll \omega_0 \ll E_1$  (here  $\omega_0$  is the oscillation frequency within a single well), and with the inter-well tunneling amplitude  $\Delta \sim |E_1 - E_2|$ . The above conditions ensure that higher eigenstates of the system are separated from the nearly degenerate doublet by a large gap (compared to  $\Delta$ ), and the probability of their excitation can be neglected. The energy difference  $|E_1 - E_2|$  is controlled by an external

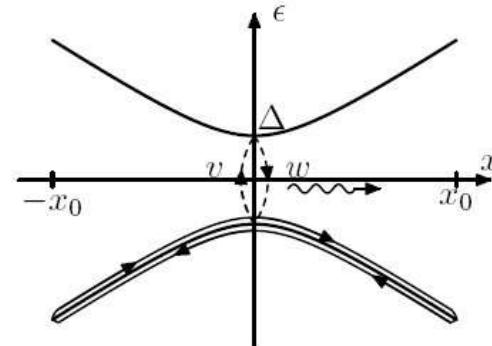
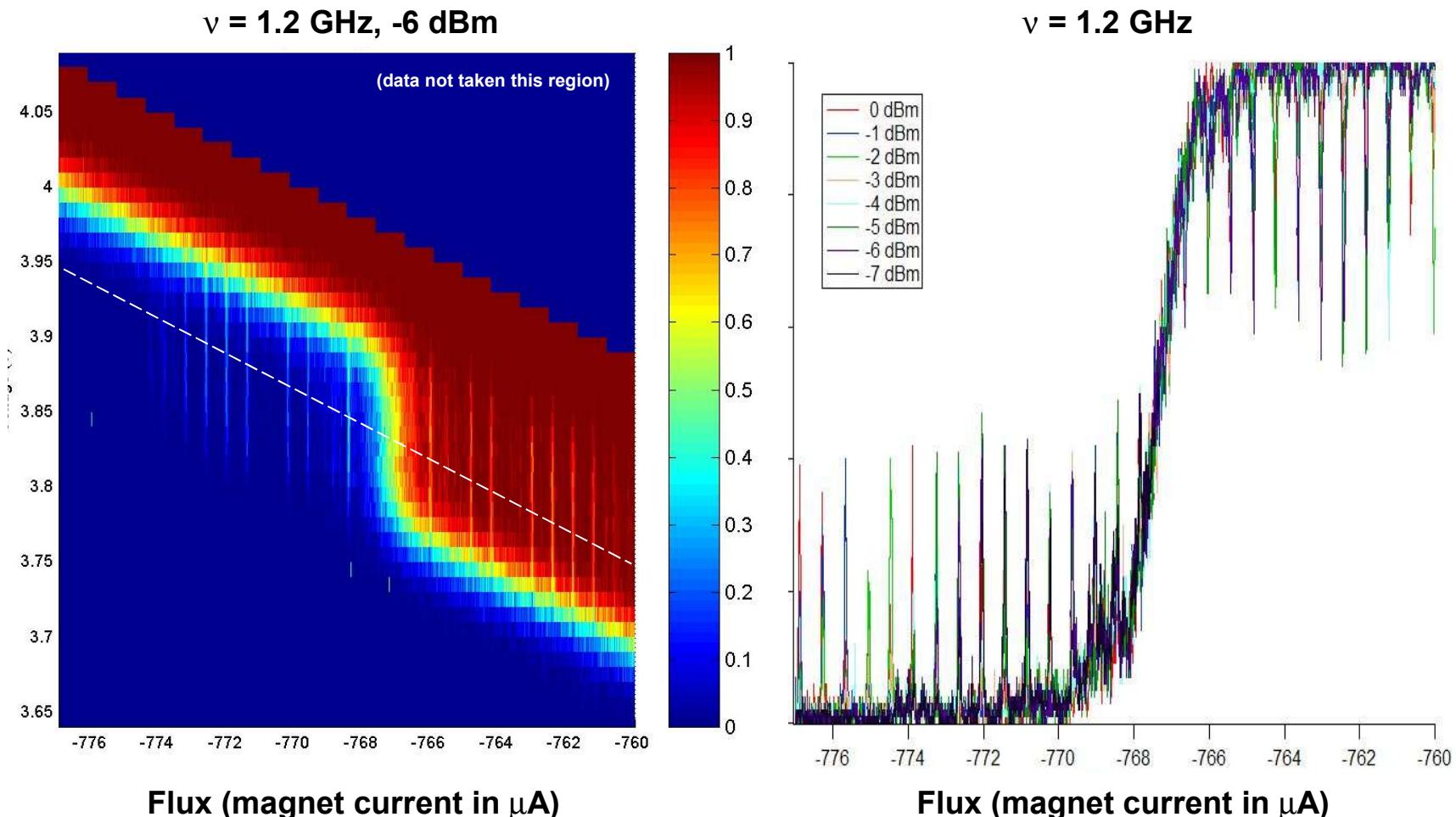
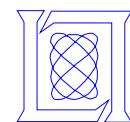
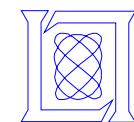


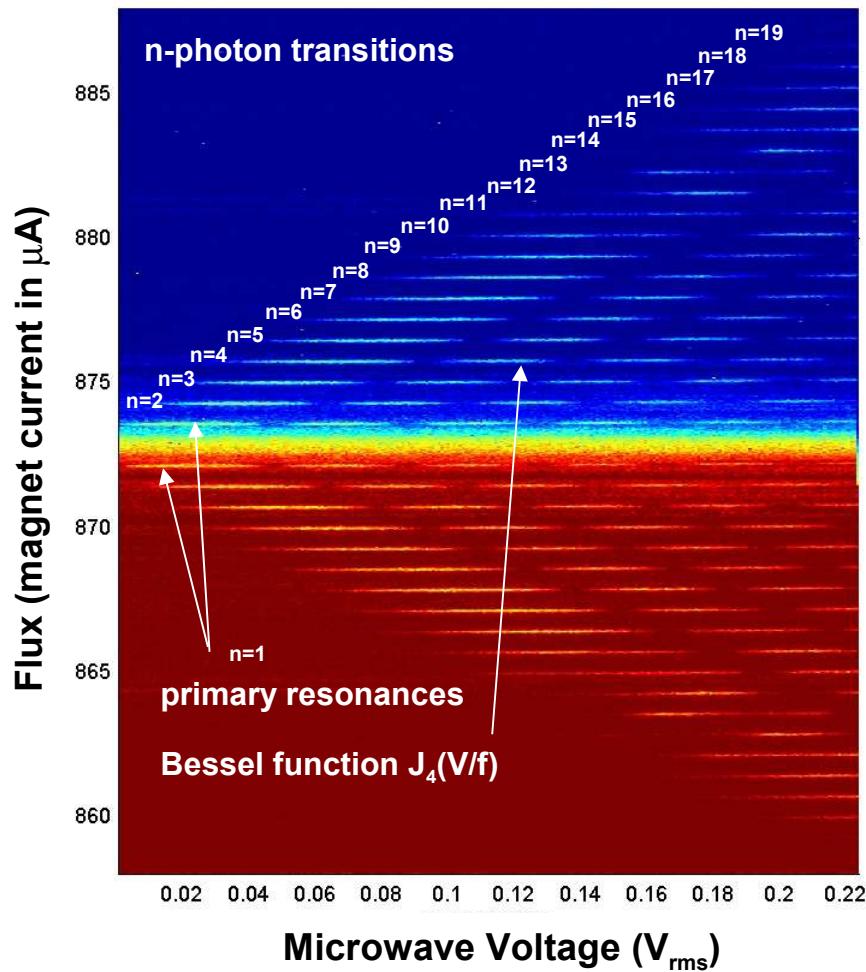
FIG. 1: Eigenvalues  $\epsilon$  of the Hamiltonian (1) depend on the control parameter  $x$ . When the control parameter passes the Landau–Zener point ( $x=0$ ), the qubit may be non-adiabatically excited with the probability  $v$ . The upper state may also decay into the lower one, dissipating the energy into

*This work: high driving frequency, nonadiabatic LZ transitions*

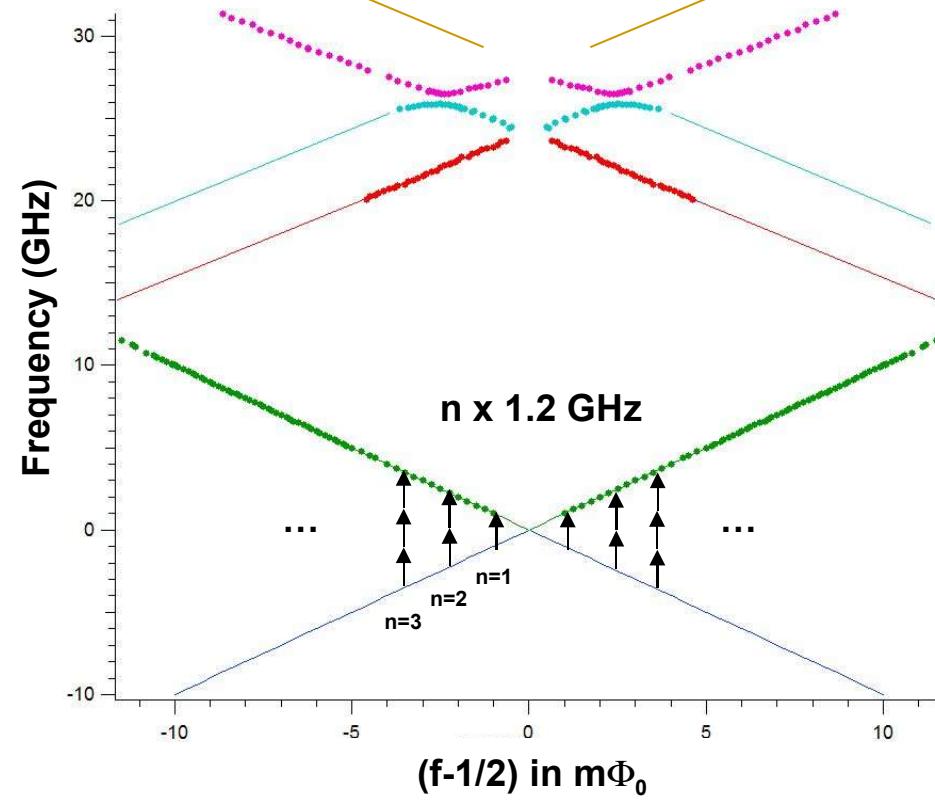


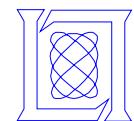


$f = 1.2 \text{ GHz}$



Qubit Energy Band Diagram





**Two-level system  
coupled to a  
classical RF field  
within the resonance  
approximation:**

$$\langle N \rangle = \langle a^\dagger a \rangle \gg 1$$

$$H = -\frac{1}{2} [\varepsilon(t) \sigma^z + \Delta \sigma^x] \equiv -\frac{1}{2} \begin{pmatrix} \varepsilon(t) & \Delta \\ \Delta & -\varepsilon(t) \end{pmatrix} \quad \varepsilon(t) = \varepsilon_0 + a \cos \omega t$$

$$\varepsilon_n = \varepsilon_0 - n \hbar \omega$$

$$H_n = -\frac{1}{2} [\varepsilon_n \sigma^z + \Delta_n \sigma^x] \equiv -\frac{1}{2} \begin{pmatrix} \varepsilon_n & \Delta_n(\lambda) \\ \Delta_n^*(\lambda) & -\varepsilon_n \end{pmatrix} \quad \Delta_n = \Delta J_n(\lambda)$$

$$\lambda \equiv \frac{a}{\hbar \omega}$$

**Small RF amplitude limit:**  $\Delta_1 = \lim_{\lambda \ll 1} \Delta J_1(\lambda) = \Delta a / \hbar \omega$  **Primary resonance**

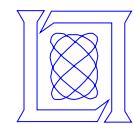
**Large RF amplitude limit:**  $\Delta_n(\lambda) = \Delta J_n(\lambda)$  **n-photon resonances**

**Generalized Rabi frequency:**  $\Omega_n(\lambda) \propto \Delta J_n(\lambda)$

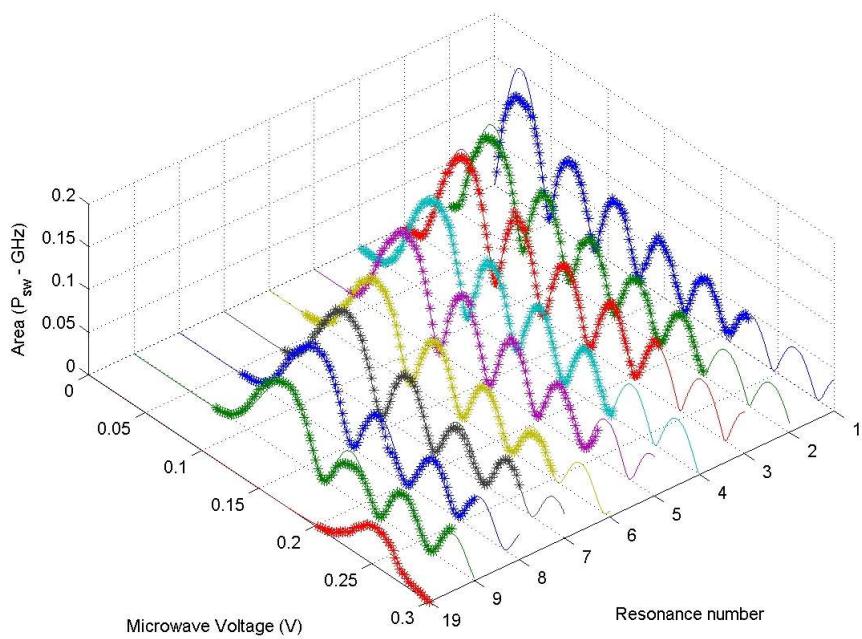
Nakamura et al., PRL 87 (2001)

Nakamura and Tsai, J. Supercond. 12 (1999)

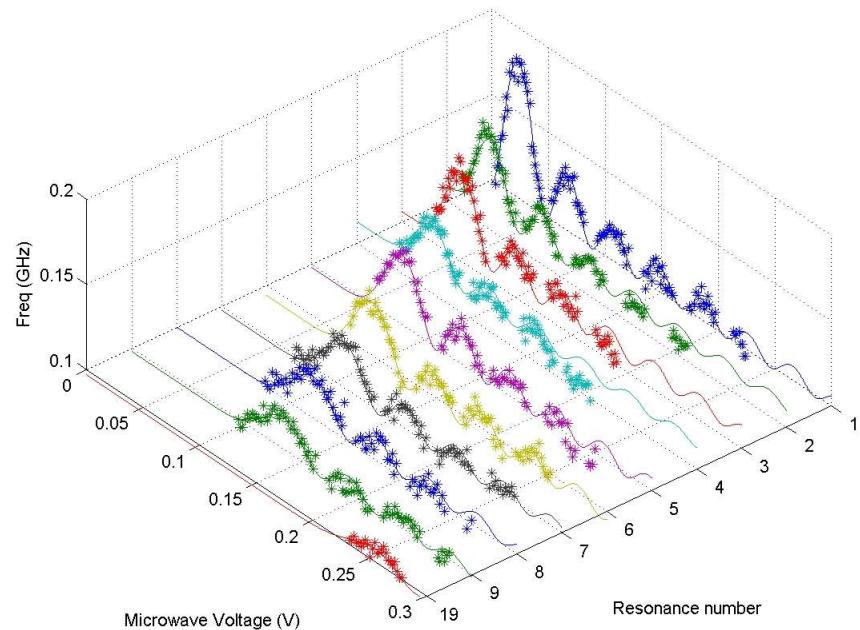
**Spectroscopy-peak area:**  $p_n(\lambda) \propto \frac{\Delta_n^2}{\sqrt{\Delta_n^2 + \Gamma^2}} = \begin{cases} |\Delta_n|, & \Delta_n^2 \ll \Gamma^2 \\ \Delta_n^2 / \Gamma, & \Delta_n^2 \gg \Gamma^2 \end{cases}$  *this work*



Resonance Area

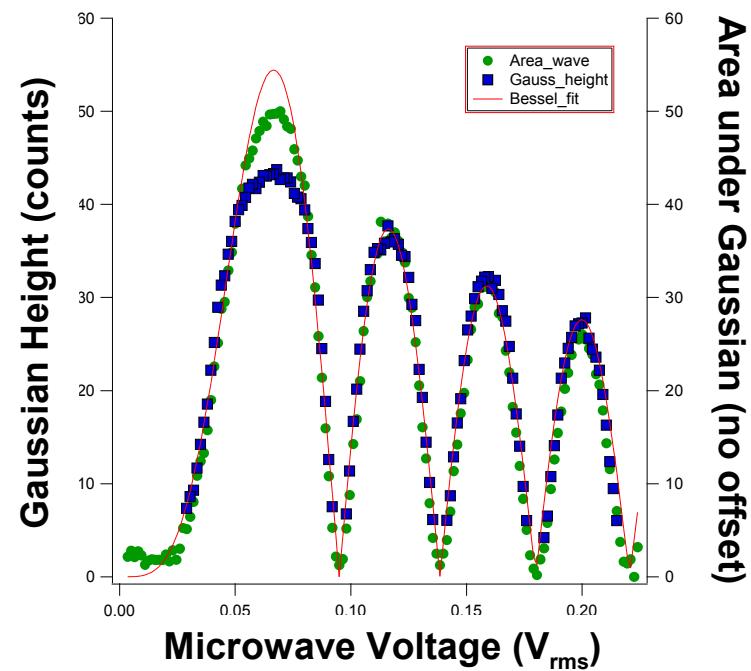
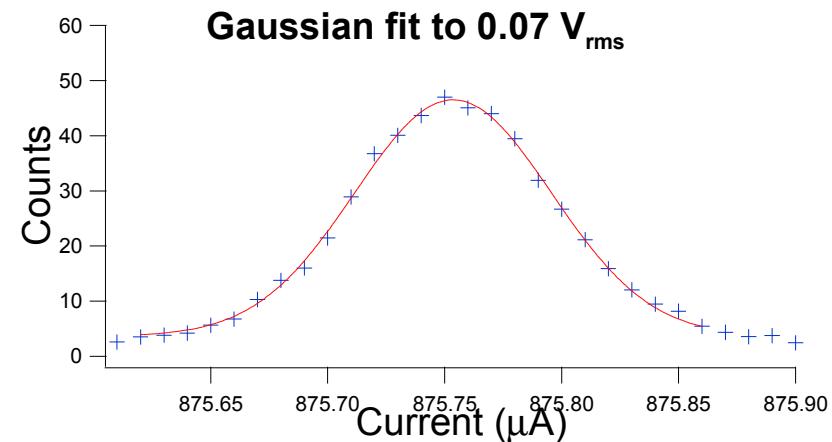
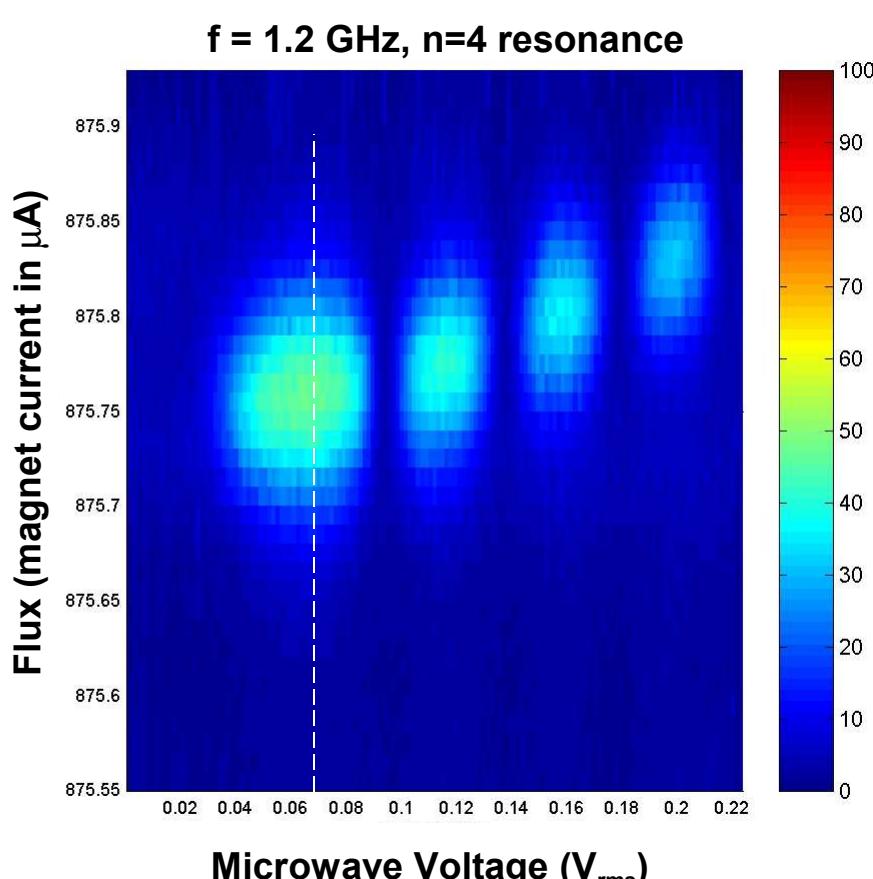
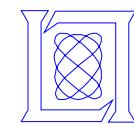


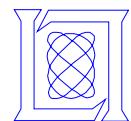
Resonance Width



$$p_n(\lambda) = \frac{\pi}{2} \frac{\Delta^2 J_n^2(\lambda)}{\sqrt{\Delta^2 J_n^2(\lambda) + \Gamma^2}}$$

$$w_n(\lambda) = \frac{2}{T_2'} + \frac{2}{T_2} \sqrt{T_1 T_2 \Delta^2 J_n^2(\lambda) + 1}$$





- .
- **Physics**
  - Quantum coherence: oscillations with RF power
  - Stuckelberg oscillations in a qubit
  - MZ fringes very well described by Bessel ladder
  - Use to find RF power on the sample, similar to Rabi osc
- **Applications**
  - Test two-level qubit model at strong driving
  - Moire patterns due to higher level anticrossings
  - Nonadiabatic control at recurrent LZ transition